The Invisible Tension of the Universe from Astrophysical Black Holes: A Solution to the Coincidence Problem of the Accelerated Expansion

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ABSTRACT

Astronomical observations have shown that the expansion of the universe is at present accelerating, consistently with a constant negative pressure or tension. This is a major puzzle because we do not understand why this tension is so small compared to the Planck density; why, being so small, it is not exactly zero; and why it has precisely the required value to make the expansion start accelerating just at the epoch when we are observing the universe. The recently proposed conjecture by Afshordi that black holes create a gravitational aether owing to quantum gravity effects, which may be identified with this invisible tension, can solve this coincidence problem. The fact that the expansion of the universe is starting to accelerate at the epoch when we observe it is a necessity that is implied by our origin in a planet orbiting a star that formed when the age of the universe was of the same order as the lifetime of the star. This argument is unrelated to any anthropic reasoning.

1. Introduction

Observations of the Cosmic Microwave Background and other astronomical distance determinations have convincingly demonstrated that the expansion of the universe started accelerating at a recent epoch (see Komatsu et al. 2010 and references therein). All of the available observations are consistent with a cosmological constant, or the effect of a constant negative pressure with value (we use Planck units with $c = \hbar = G = 1$ throughout this paper)

$$p_\Lambda = -\frac{3H_0^2}{8\pi}\Omega_{\Lambda 0} = (1.3 \pm 0.1) \times 10^{-123} \ . \tag{1}$$

Here, H_0 is the value of the Hubble constant at present and $\Omega_{\Lambda 0}$ is the ratio of the negative pressure to the critical density of the universe, and we have used the values obtained by

Komatsu et al. As far as one can tell, this value of the invisible tension of the universe appears to be a fundamental, dimensionless constant of nature, unrelated to any other known physical law. Its extremely small value, and the fact that this value is precisely the required one to cause the acceleration of the expansion of the universe to start at the epoch when we are observing it, is the major puzzle that is referred to as the coincidence problem.

There is only one other fundamental (and independent), dimensionless physical constant of nature that is different from unity by many orders of magnitude: this is related to the extreme weakness of the gravitational interaction compared to all other fundamental interactions (the ratio of neutrino to baryon masses may be considered another small number, but we will ignore neutrino physics here). For example, the ratio of the attractive gravitational and electric forces between a proton and an electron (of masses m_p and m_e) is

$$\frac{m_p m_e}{\alpha} = 4.4 \times 10^{-40} \ , \tag{2}$$

where α is the fine structure constant of the electromagnetic interaction.

There are only two possibilities: either there is some relation between these two very small constants of nature arising from some yet unknown physical law, or there is not. If there is no relation, then we have to reach the conclusion that our universe is characterized by two numbers that are extremely small for two different reasons. The hope for a simple description of the universe may lead one to suspect that there is a relation, and if so, that an explanation for the coincidence problem might be found in this relation.

It is pointed out in this paper that this is precisely the implication of the recent conjecture by Afshordi (2010), that the invisible tension of the universe may be a result of quantum gravity effects from the entropy of astrophysical black holes, which I outline briefly in §2. The reason why this conjecture predicts that the expansion of the universe starts accelerating when the age of the universe is of the same order as the lifetime of a star is then explained in §3. This argument was previously discussed in Miralda-Escudé (2007), where it was presented as an April fool's day joke instead of the standard scientific format, attributing the reason for a relation between the two very small fundamental physical constants of nature to made-up nonsense, as part of the joke.

2. Gravitational aether and astrophysical black holes

Afshordi (2010; see also references therein) postulates a model of emergent gravity, in which Lorentz symmetry is an emergent phenomenon at low energies rather than a fundamental symmetry of nature. This introduces a gravitational aether which, in the presence

of quantum corrections from a black hole horizon, may acquire a finite pressure. A generic first-order finite temperature quantum correction for the relation of the black hole entropy and mass to the temperature leads one to conclude, via the first law of thermodynamics, that the quantum correction implies a gravitational aether pressure

$$p = -C_a \pi T_{bh}^3 \ , \tag{3}$$

where C_a is a dimensionless constant that would depend on the quantum gravity theory, T_{bh} is the black hole horizon temperature, and the black hole mass is $m_{bh} = (8\pi T_{bh})^{-1}$.

In the presence of many black holes in the universe, it was argued by Prescod-Weinstein, Afshordi & Balogh (2009) that the pressure of the gravitational aether should settle to an approximate hydrostatic equilibrium over most of the volume in between the black holes, to a value that corresponds to a mean black hole mass, $\bar{m}_{bh}$, equal to the mass-weighted geometric average of all the black holes in the universe. Because most of the mass density in black holes is contributed by the remnants of core collapse of massive stars, this mean black hole mass should be not much larger than that of the typical black hole formed from a single star, which is a few times the Chandrasekhar mass.

3. Solution to the coincidence problem

The Chandrasekhar mass, m_{Ch}, for a star made of $N_{Ch} = m_{Ch}/m_p$ baryons, beyond which a degenerate star must collapse to a black hole, is obtained from the condition that the degenerate energy of the particles at the point when they become relativistic balances the gravitational energy of the star. The maximum degeneracy energy of the particles in a star of radius R is $\sim N_{Ch}^{1/3}/R$, while the gravitational energy is $\sim m_{Ch}^2/R$. Equating the two results in $m_{Ch} \simeq m_p^{-2}$. Therefore, we can write $\bar{m}_{bh} = C_{bh}/m_p^2$, where C_{bh} is a constant that is not much larger than one, since the typical black hole made by the collapse of stars has a mass that is not much more than a few times the Chandrasekhar mass.

The pressure of the gravitational aether is then

$$p = -\frac{C_a \pi m_p^6}{(8\pi C_{bh})^3} \ . \tag{4}$$

This is the relation we have in this model between the two very small constants of the universe, provided that C_a and C_{bh} are not themselves extremely different from unity. The age of the universe when this negative pressure becomes dynamically dominant for the expansion is

$$t_e = \left(\frac{3}{8\pi|p|}\right)^{1/2} = \frac{8\sqrt{3\pi} C_{bh}^{3/2}}{\sqrt{C_a} m_p^3} \ . \tag{5}$$

We are now interested in comparing this time to the lifetime of a star. The lifetime can be expressed in terms of the efficiency of generating energy from nuclear reactions, ϵ, and the fraction of the Eddington luminosity at which the star radiates energy, ℓ. The Eddington luminosity of a star of mass M is given by

$$L_{Edd} = \frac{3\mu_e m_e^2}{2\alpha^2} M \; , \tag{6}$$

where μ_e is the mean mass per electron ($\simeq 1.2 m_p$ for the fully ionized primordial mixture of hydrogen and helium). The stellar lifetime is

$$t_s = \frac{M\epsilon}{\ell L_{Edd}} = \frac{2\alpha^2 \epsilon}{3\ell \mu_e m_e^2} \; . \tag{7}$$

Hence, the ratio of the age of the universe to the stellar lifetime when the cosmic acceleration starts is

$$\frac{t}{t_s} = \frac{12\sqrt{3\pi C_{bh}^3} \, \ell \mu_e m_e^2}{4\alpha^2 \epsilon \sqrt{C_a} m_p^3} \; . \tag{8}$$

This solves, at least in part, the coincidence problem: the ratio of the age of the universe to the stellar lifetime does not depend on the extremely small values of the particle masses (reflecting the weakness of gravity when we use Planck units). It is therefore not so surprising that the two times turn out to be comparable, even though they still depend on quantities that are far from unity: the ratio of the electron to proton mass, the fine-structure constant, the efficiency of nuclear reactions, and the fraction of the Eddington luminosity at which a certain star radiates. The fraction ℓ is close to unity for massive stars, it is $\ell = 10^{-4.6}$ for the Sun, and drops to $\ell \sim 10^{-7}$ for the lowest mass stars that are still able to ignite nuclear reactions.

4.   Discussion

The conjecture proposed by Afshordi (2010) that the invisible tension in the universe arises from a gravitational aether that acquires a negative pressure from the existence of astrophysical black holes implies that this invisible tension scales as m_p^{-6}. This provides an automatic explanation for why the acceleration of the expansion of the universe is starting close to the epoch when we observe it. It is still surprising that the combination of constants appearing in equation (8) is roughly close to unity for a star like the Sun, but this coincidence now seems much less unlikely than in the case when the two very small fundamental constants of nature are unrelated.

It should be noted that this explanation for the coincidence problem is unrelated to the anthropic principle. The prediction that the expansion should start accelerating when the

age of the universe is of the same order as the lifetime of a star is a purely physical one and bears no relation to our presence in the universe. The fact that the lifetime of the Sun and the present age of the universe are comparable is known to be true, and it has not been considered a surprising coincidence: this may be related to a "weak" and obvious form of t anthropic principle that says that we must appear in the universe at the epoch when most of the stars adequate for harboring planets with life are in their main-sequence phase.

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